Module 1
Frameworks for Analysis of Land and Environment in the Arctic

Developed by Karen Erickson, Assoc Prof, Political Science Department, University of Alaska Fairbanks; and Kimberly Ognisty, B.A. Language Studies: Political Science, University of Alaska Fairbanks

Key Terms and Concepts

- Arctic haze
- biocomplexity
- biodiversity
- biogeochemical cycle
- carbon cycle
- carrying capacity
- complex systems
- deposition
- ecosystem
- glacier
- gyre
- hydrological cycle
- ice fog
- mid-ocean ridge
- nitrogen cycle
- North Atlantic Oscillation
- organizational scale
- ozone
- Pacific Decadal Oscillation
- phosphorus cycle
- photosynthesis
- plate tectonics

- predation
- primary productivity
- radionuclide
- spatial scale
- subduction zone
- sulphur cycle
- sustainability
- temporal scale
- trophic level

Learning Objectives/Outcomes

Upon completion of this module, you should be able to

1. become familiar with environmental terms that are especially applicable in the Arctic context.
2. understand key applications of science and to use a systematic approach in analyzing land and environment in the Arctic.
3. learn how the atmosphere serves as a contaminant pathway linking all regions of the globe.
4. understand the relationship between the ocean and global climate patterns.
5. recognize the processes and functions of the Earth systems and their environmental significance.
6. appreciate the distinctive components and vulnerabilities of the Arctic ecosystem.
7. understand the importance of the relationships between science and policy, with special respect to resource depletion and ecological contamination.
8. analyze the impacts of environmental changes on human health and culture.
9. gain knowledge of long-term stewardship and the major principles of ecology and international environmental law.

Reading Assignments

Part I

Rachel Carson (1962), *Silent Spring* (Boston: Houghton Mifflin).

Brundtland Commission (1987), *Brundtland Report: Our Common Future*, World Commission on Environment and Development (Oxford: Oxford University Press), chapters 1 and 2, pages 1–66.

Part II

Conservation of Arctic Flora and Fauna (CAFF 2001), *Arctic Flora and Fauna: Status and Conservation*, Chapter 8: "The Oceans and Seas," pages 183–209, [online] http://www.caff.is/.

Part III

Mark Nuttall and Terry V. Callaghan, eds. (2000), *The Arctic: Environment, People, Policy* (Amsterdam: Harwood Academic), Chapter 20, pages 575–600.

Part IV

Brundtland Commission (1987), *Brundtland Report: Our Common Future*, World Commission on Environment and Development (Oxford: Oxford University Press), Annex 1, pages 348–351.

Brent S.Steel, Richard L. Clinton, and Nicholas P. Lovrich, Jr. (2003), *Environmental Politics and Policy: A Comparative Approach* (Boston: McGraw Hill Publishers), Chapter 2: "Brief Introduction to the Science of Ecology," pages 61–70.

Overview

The application of scientific knowledge is essential in order to improve the human condition. This is especially true in the Arctic. Science draws on the wisdom of generations and constantly synthesizes new information in order to explain land and environment relations in the circumpolar North. How do environmental factors affect habitat? What role do human beings play in sustaining the Arctic ecosystem? How is human health linked to environmental change in the Arctic?

Land/environment conditions in the Arctic can be systematically studied in order to understand the interactions of a vulnerable ecosystem. As tools of analysis, we enlist multiple disciplines and the perspectives of time, size, and complexity of the organism to explain patterns of ecological activity. The biocomplexity of the Arctic is linked to the global ecosystem, and no discussion of the future of the planet is complete without including the Arctic.

Characteristic of a cold-climate ecosystem, the Arctic is particularly fragile, sensitive to disturbance, and susceptible to toxic accumulation. The result is that the Arctic is vulnerable to human input, making it as necessary to understand how to manage the environment and natural resources as it is to know the basic science. How does the interaction of human and natural processes affect the capacity of natural systems to meet human resource needs and to support the quality of life? Of primary importance in maintaining sustainability in the Arctic is addressing resource depletion and environmental contamination. The Arctic is a young region in terms of economic development and is therefore seen as a source of resource extraction. The vulnerability of the region is also found in the threat of contaminants. The cooler regions of the poles tend to accumulate the pollutants from lower latitudes, with no mechanism to transport them out of the Arctic region.

The important issues of science and policy in the Arctic are illustrated in a case study of Amchitka Island, where cold-war radionuclides in the marine environment and food web are particularly destructive to environment and habitat. How can sound science be applied in developing a stewardship plan for Amchitka? Amchitka illustrates the complexity of ecological issues and the significant impacts of system disturbance on the livelihood of cultures that depend on subsistence.

The search to maintain our eco-*systems*-based survival (sustainability) and to determine the most effective means of achieving that goal (long-term stewardship) lies at the heart of understanding science-based policy. What are the fundamental ecological principles of sustainability? How might we determine the important principles of management for long-term stewardship? Guiding principles for management and policy choices regarding human/environment issues are found in the conventions and practices of international law, together with an emerging global consensus on the means to plan for the stewardship of the planet.

Lecture

Frameworks for Analysis of Land and Environment in the Arctic

What do people need to know in order to live well in the Arctic? Science is an important tool for understanding conditions and dynamics in sensitive regions like the Arctic. It is equally important to understand applications of scientific knowledge, and to work with integrated ideas of theory and practice that have prevailed from generation to generation among Arctic inhabitants. Science is a dynamic process that constantly synthesizes new ideas, methods, and information in order to explain the wide array of land and environment interrelationships.

Part I: Environmental Terminology

A number of concepts that relate to the scientific study of the environment are increasingly significant in comprehending nature and life in the Arctic. Some of the following terms are used interchangeably and should therefore be clarified: ecosystem; biodiversity; complex systems; biocomplexity; and sustainability.

The concept of *ecosystem* may be the oldest and singularly most important basis for explaining environmental relationships. As early as 1935, an ecosystem was identified as a wide range of habitat factors, much more inclusive than simply organisms (Tansley 1935). Ecosystems are self-sustaining entities that exist in many sizes and variations, from the global ecosystem to a small lake ecosystem. A useful definition of ecosystem is

> A holistic concept of the plants, the animals habitually associated with them, and all the physical and chemical components of the immediate environment or habitat which together form a recognizable self-contained entity (Begon et al. 1996).

Biodiversity refers to the diverse forms in which organisms have evolved. Three levels of diversity are normally considered:

- *genetic diversity*—variations in genes enabling organisms to evolve and adapt to new conditions
- *species diversity*—the number of species and distribution of species within an ecosystem
- *ecosystem diversity*—the variety of habitats and communities of different species that interact in a complex web of relationships (Biodiversity Resource Center 2003)

Biodiversity emerges from many levels of biological organization, from the paramecium to the polar bear, as a result of evolution and natural selection. Biodiversity is the key factor in maintaining the health of an ecosystem. In 1996, the Ottawa Declaration on the Establishment of the Arctic Council called on the members to commit to the "maintenance of biodiversity in the Arctic region."

Growing knowledge of diversity among biological species has expanded the field of inquiry into land and environment relationships and how they function. *Complex systems* are environmental relationships and feedbacks as they occur on different scales of time, locale, and organization. Complex systems can be demonstrated, for example, in the relationship between oceans and the atmosphere. The concept of complex systems is also a basis for explaining human/environment relationships in a comprehensive manner. By synthesizing traditional fields of research and applying multidisciplinary perspectives, complex systems analysis aids in the understanding of how "humanity has intervened on the scale of the system in the operation of planet earth" (Schellnhuber 1998).

Complex systems are the basis for studying *biocomplexity*, the interaction of biological, chemical, social, and economic systems (Colwell 1998). The notion of biocomplexity is deep-seated in Rachel Carson's seminal work, *Silent Spring* (1962). By observing the wide range of interrelationships that reflect the "web of life," Carson pointed out the significance of making connections between facts that were apparently unrelated. Environmental relationships involve many more variables than are taken into account by simple cause-and-effect reasoning. Given that interactions between human and non-human populations display non-linear behaviour, a holistic perspective is needed for an accurate picture of environmental development.

The holistic view of environmental interactions and impacts is significant for understanding the process of *sustainability*, the maintenance of an ecologically sound, economically feasible, and socially just biosphere (Lubchenco 1998). Sustainability lies at the core of a healthy ecosystem because it assumes (1) system stability under the force of change in human/environment relationships and (2) controlled balance in the face of rapid growth and development. Succinctly stated, "sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future" (Brundtland Commission 1987). Sustainability, as a natural process, is increasingly affected by the tentative interrelationships between human beings and the environment.

These environmental terms will be useful in comprehending basic questions that are raised throughout this course. How do systems respond to change? What types of systems are more resilient to change? How do systems adapt to stress or disruptions? How do environmental factors affect habitat? To what extent are socio-economic conditions affected by climate change? What role do human beings play in sustaining the Arctic ecosystem? How is human health linked to environmental change in the Arctic? An understanding of environmental terminology is equally important when questions of science are linked to management and policy issues. How is a healthy ecosystem to be managed? What policies are necessary in order to promote sustainable development and environmental protection? The answers are guided by fundamental concerns for long-term stewardship of the land and environment.

Student Activity

Visit a government or community agency in your area to find out ways in which the work of that agency promotes sustainable development and environmental protection.

Part II: The Systematic Study of Land and Environment

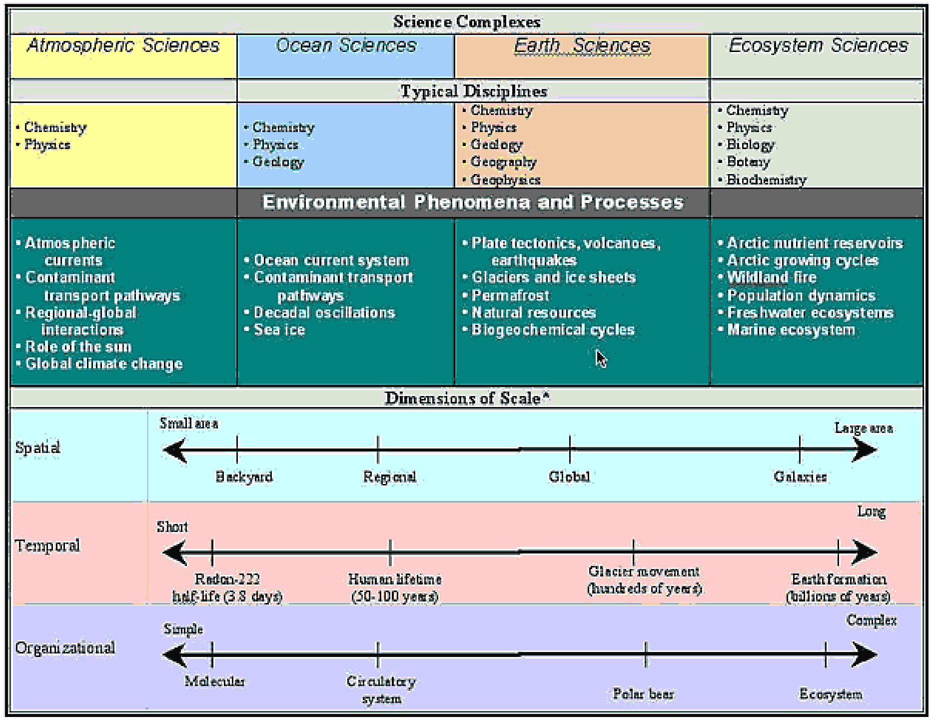
Land/environment conditions in the Arctic can be studied in a number of ways. Figure 1.1 suggests a framework for analyzing environmental interactions. Environmental phenomena and processes can be understood through the disciplines of science and with the help of different types of scales that denote time, locale, and degree of organization. The disciplinary perspectives are organized into four broad sets, or *science complexes*: atmospheric sciences; ocean sciences; Earth sciences; and ecosystem sciences. Single disciplines typically make up the more inclusive science complexes (several *typical disciplines* are listed in figure 1.1). Disciplinary perspectives play a key role in the analysis of complicated environmental systems.

The *dimensions of scale* may require further elaboration. Scale analysis allows scientists to consider a more complete, multi-dimensional view of complex systems. *Spatial scales* are a gradient from as small as a backyard to as large as galaxies; including an infinite range of intermediate locales, such as regional and global. *Temporal scales* are the differing time frames in which the many processes and organisms exist on Earth. Variation in the temporal scale ranges from seconds, in the case of the half-life of the radioactive isotope radon-222 to the billions of years for the formation of Earth. *Organizational scales* are the structural organization of various components of a system. Organizational scales may be as simple as the molecular structure of water and as complex as an entire ecosystem.

The perspectives of multiple disciplines and scale levels combine to help scientists create, for example, a more comprehensive picture of the role of water on Earth. Although it's a simple molecule, water cycles through many reservoirs (the ocean, atmosphere, lakes, rivers, sea ice, permafrost, groundwater, and organisms) and serves a variety of functions within the environment. The flow and function of water is otherwise known as the *hydrological cycle*.

In order to fully understand the hydrological cycle, we need to draw on the expertise of several disciplines. A *geologist* can describe how the ocean has created a sedimentary rock formation or how a small river carved a massive canyon, like the Grand Canyon. A *chemist* can describe how water carries essential elements such as carbon and nitrogen through their own cycles, providing organisms with essential nutrients. A *physicist* can describe the invisible forces holding a water molecule together and its transformation among solid, liquid, and gaseous stages. A *biologist* can describe how water itself is a basic premise for life on Earth and the role it plays in complex life forms like orcas.

An analysis of the hydrological cycle also employs different dimensions of scale: (1) *spatial*: the entire water cycle covers the globe, while permafrost spans only a regional area; (2) *temporal*: components of the water cycle, such as the evaporation of water and the subsequent precipitation, can occur in the time frame of a few days, whereas water stored in sea ice spans a time frame from decades to hundreds of years; (3) *organization*: organizationally, water is quite simple, composed of two hydrogen atoms and one oxygen atom to form one water molecule. Although it is a simple molecule, water is also involved in complex life forms like polar bears.



* Spatial, temporal, and organizational divisions of scale have been identified by the National Science Foundation as characteristics of complex systems.

Source: Developed by Erickson and Ognisty (2003)

Fig. 1.1 Framework for study and analysis of environmental interactions in the Arctic

Atmospheric Sciences

The atmospheric sciences study the role of the atmosphere as a global reservoir. Atmospheric scientists primarily use chemistry and physics to investigate the flux of essential nutrients in the atmospheric portion of the biogeochemical Earth cycle. The atmosphere protects living organisms from solar radiation and keeps the temperature at the surface of the Earth livable. The global air current systems shape local weather pattern and distribute essential elements and contaminants throughout the globe.

The global climate patterns of the Earth are largely determined by the input of solar energy and the movement of the planet in space. About half of the solar energy that reaches the upper layers of the atmosphere is absorbed before it reaches the Earth. Much of the energy that strikes Earth itself is absorbed by land and water, while some is reflected back into the atmosphere. The warming effect of the Sun on the atmosphere, land, and water establishes temperature variations, cycles of air movement, and evaporation of water that are responsible for latitudinal variations in climate.

Intense solar radiation near the equator initiates a global circulation of air, creating precipitation and winds. High temperatures in the tropics evaporate water from Earth's surface and cause warm, wet air masses to rise and flow towards the poles. The high-altitude air masses, now dry, descend toward Earth at latitudes around 30^{o} north and south, absorbing moisture from the land and creating an arid climate. Around the Earth, large expanses of desert will be found at these latitudes. Some of the descending air flows towards the poles at low latitude, establishing a midlatitude circulation cell that deposits abundant precipitation where the air masses again rise and release moisture near 60^{o} latitude. This latitude corresponds with increased precipitation regions in southeast Alaska, Canada, Russia, Finland, Sweden, Norway, Iceland, and Greenland. A third circulation cell carries some of the cold, dry rising air to the poles, where it descends and flows back toward the equator, absorbing moisture and creating the relatively rainless, cold climate of the Arctic.

In the northern hemisphere, wind patterns high in the atmosphere are known as the *jet stream* and flow from west to east. An example of the effect of this wind current system is a long-distance airplane flight. A flight from Los Angeles to Washington DC, heading east with the wind helping to propel the plane, is always shorter than a flight from Washington DC to Los Angeles because, on its way to Los Angeles, the plane is flying against the current, which takes more time and energy. In the Arctic region, this high-altitude current is important because it is capable of carrying contaminants thousands of miles.

Surface wind currents, however, flow in many directions depending on the daily effects of temperature, pressure, and topography. Each region has a generally predictable cycle and direction of winds throughout the year. The day of the Chernobyl nuclear power plant accident, for instance, the winds in the region were blowing in an easterly direction. As a result, large areas of northern Europe received contaminated precipitation following the accident.

The atmosphere is primarily composed of nitrogen and oxygen with smaller amounts of argon, carbon dioxide, and water vapour. Any element has the potential to be taken up by the global air currents if its size and mass are similar to other airborne particles. There are several mechanisms for *vaporization* and *sublimation* (the transformations of a liquid or solid, respectively, into a gas). When a volcano erupts, much of its emission is in a gaseous form, including sulphur, which is introduced into the atmosphere. In the combustion of gasoline to produce energy, cars vaporize various elements, primarily carbon monoxide, before emitting them. Manufacturing plants emit by-products of energy production and any chemicals used in the manufacturing process. Until atmospheric nuclear tests were banned, vaporized radioactive isotopes were taken up by the air currents during nuclear tests.

There are mechanisms for removing contaminants from the air currents. The first is *deposition*, which clears particulate matter from the air and deposits it on the ground. As a result of this mechanism, regions of the world with high levels of precipitation receive wet deposition containing contaminants that originated in another part of the world. In the circumpolar North, southeast Alaska and the Pacific coast of Canada receive high levels of radioactive isotope deposition from atmospheric nuclear testing.

Another example of removing contaminants from the air is the result of cooler temperatures. In cooler temperatures the particulate load that the air can carry diminishes and larger, heavier particles drop out of the current system. Particulate matter from Chinese coal plants, for example, has been identified in interior Alaska as a result of dry deposition (Wetzel et al. 2003). Because the air in the circumpolar North does not warm significantly relative to the lower latitudes, there is no reverse mechanism to send particulate matter from the Arctic to other regions of the world. As a result, the Arctic is susceptible to accumulating an undue share of non-local contaminants.

Arctic haze and *ice fog* are two examples of contaminated air in the Arctic from both global and local sources. Fossil fuels with high sulphur content produce sulphur dioxide when they burn. In the atmosphere, the sulphur dioxide reacts with hydroxyl radicals (OH^- ions), creating sulphuric acid. In the cold air of the High Arctic, the main components of Arctic haze are sulphuric acid in the form of tiny particles. Sulphur compounds also enter the atmosphere from plankton and volcanoes. The rates of different chemical reactions in the sulphur cycle depend on energy from the Sun. In the Arctic, lack of sunlight during the polar winter limits production of the hydroxyl radical, which slows the production of sulphuric acid. When the Sun returns in the early spring, there is a load of sulphur dioxide in the air, ready to be converted into sulphate aerosols. This photochemical mechanism explains why Arctic haze is most pronounced in March and April, after the Arctic sunrise. Measurements of air concentrations of sulphur dioxide are highest over the Kola Peninsula and northern Fennoscandia, primarily as a result of European emissions. Ice fog occurs as a result of inversions in many localized regions of the Arctic. In Arctic regions with higher emissions from vehicles or manufacturing, the emissions become frozen with water molecules in the fog. Upon inhalation, the warmth of a living organism melts the ice and small amounts of water and contaminants are inhaled internally or coat other living organisms, such as plants.

On a global scale, the release of certain chemicals into the atmosphere has resulted in the destruction of the *stratospheric ozone layer*, 12–50 kilometres above the surface of the Earth. *Ozone* can be considered good or bad, depending on its location in the atmosphere. In the *troposphere*, the lower atmosphere, ozone is a major component of smog. Because ozone is an extremely powerful oxidizing agent, it is highly toxic to animals and humans, while it slows the rate of photosynthesis in plants. In the stratosphere, however, ozone blocks 95–99% of ultraviolet-B (UVB) radiation from the Sun. Ozone has been thinning throughout the world, with distinct holes developing seasonally over the Arctic and the Antarctic. UVB radiation is harmful to both health and the environment. UVB leads to increased risk of skin cancer and cataracts in humans, while it suppresses the body's immune system, making it more vulnerable to certain diseases. The growth of many plants has been inhibited in laboratory experiments with excess UVB radiation. It also causes developmental abnormalities in amphibians. UVB radiation has been identified as a source of reduced productivity of phytoplankton, the base of the ocean's food web.

While the Arctic is still considered clean relative to much of the world, contaminants introduced into the air in the midlatitudes have a significant effect on the circumpolar North. Some of these contaminants have been cited as anthropogenic sources of global warming and climate change, which are having a considerable effect on the ice pack, glaciers, and tundra regions of the Arctic. Others are creating an ozone hole over the Arctic or are physically being deposited in the Arctic. The deposition of air contaminants can subsequently affect berries, mushrooms, and lichens, and can be swept into the water systems.

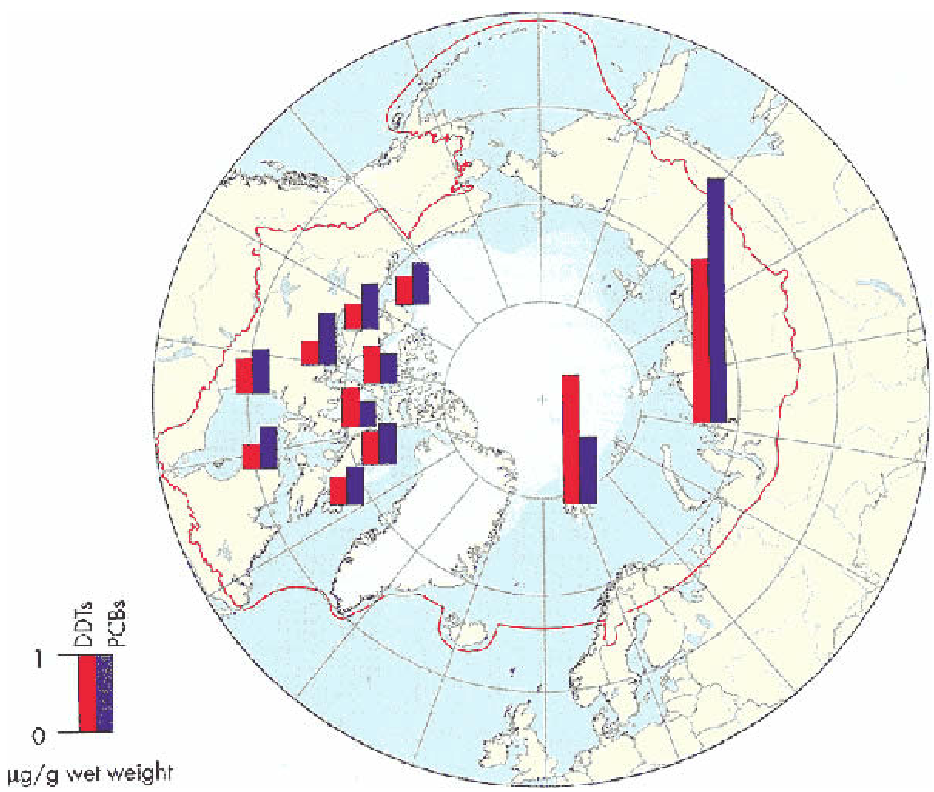
Ocean Sciences

The ocean sciences study complex interactions between the oceans, the land, and the atmosphere. They use chemistry, physics, biology, and geology to learn why changes in temperature in the ocean affect the entire global climate system. The structure of the Arctic Ocean and its marine ecology are susceptible to dramatic changes as a result of changes in the global climate system. The Arctic marine environment is also vulnerable to contaminants travelling on ocean currents as far away as the equator.

Wind, tides, and gravity create a dynamic global *ocean surface current system*. Currents move large amounts of water and nutrients great distances, flowing in large rotating loops called *gyres*. Gyres in the northern hemisphere spin in a clockwise direction, while gyres in the southern hemisphere spin in a counter-clockwise direction, a phenomenon known as the *Coriolis effect*. There is also a separate deep ocean current system that is created when warm, salty North Atlantic water reaches the cold Arctic near Greenland and Iceland and becomes denser as it cools, eventually sinking to the deeper layers of the ocean.

The size of the oceans and the quantity of water housed in them is enormous. While direct ocean pollution has occurred in localized regions of the oceans, on a worldwide scale the oceans are incredibly resilient. The oceans are so large that incredible concentrations of pollutants can be diluted to low concentrations posing little risk to ecological health. There are certain classes of pollutants, however, that pose significant threats to the resources of the ocean. *Persistent organic pollutants* (POPs), *polychlorinated biphenyls* (PCBs), and *radioactive isotopes* are such long-lived pollutants that they can travel great distances on ocean currents. Because of the chemical composition of some of the pollutants, they can readily be biologically taken up by fish and marine mammals and enter specific human organs upon ingestion, including bone marrow, the blood stream, or mother's milk.

Radionuclides pose both a short- and long-term threat because of the variation in decay rates. Some radionuclides such as cesium-137 have a half-life of approximately 30 years, while others such as plutonium have a half-life of millions of years. POPs and PCBs are especially dangerous because the chemicals do not break down. Because both are fat-soluble, they accumulate in fatty tissues and affect mammals higher on the food chain, including humans, polar bears, and sea lions. This is a potential source of concern for Arctic peoples living on subsistence diets that depend heavily on high-energy, high-fat foods. Figure 1.2 illustrates the concentrations of DDT and PCBs in the blubber of female ringed seals. DDT is an insecticide that has been banned in the United States for more than 30 years. It is still appearing in the Arctic because of the lag time—the period of time it takes a pollutant to travel from the source at a middle latitude to the high latitude of the Arctic.



Source: Nakata et al. (1998), in CAFF

Fig. 1.2 Concentrations of DDTs and PCBs in the blubber of female ringed seals in the 1980s and early 1990s

The interaction between the oceans and the atmosphere is very important in the understanding of complex systems, including global climate change. The oceans are having an identifiable effect on climate change through decadal cycles of ocean warming and cooling in large regions. With these changes in temperature come regional climate fluctuations and changes in the marine resource base. The *Pacific Decadal Oscillation* affects coastal surface temperatures from California to Alaska and is thought to affect the survival of fish stocks in the area. The oscillation is a change in current associated with changes in atmospheric pressure, winds, precipitation, and water temperature. Cold and wet conditions are associated with southerly current flows, and warm and dry conditions predominate with northerly flows. Regional decadal cycles off the Oregon and Washington coast and near Bristol Bay, associated with the Pacific Decadal Oscillation, have been blamed for low salmon runs in the Yukon Delta. The extremely low runs affect subsistence dieters farther up river as well as the commercial fishing industry, thereby depressing economies in the circumpolar North. The *North Atlantic Oscillation* is a result of pools of warm and cool surface water circling the North Atlantic region. The pools have life spans of four to ten years. The cooler pools are associated with harsh winters in Europe and cooler-than-average temperatures over the entire northern hemisphere.

The Arctic Ocean is supplied from the North Atlantic by the Norwegian Current and water flows via the Fram Strait and the Barents Sea. Some of this flow enters west of Spitsbergen, but most flows over the top of Norway and Finland and moves eastward along the Siberian coast into the Chukchi Sea. A small inflow of water enters the Arctic through the Bering Strait and brings water from the Bering Sea to join the eastward flow along Siberia and the large Arctic gyre. Rivers account for about 2 % of the Arctic basin water input, a high percentage compared to the rest of the world's oceans. The main outflow is via the East Greenland Current.

The density of the Arctic Ocean water is controlled more by salinity than by temperature. The surface layer is formed from low-salinity water entering from the Bering Sea, fresh water from Siberian and Canadian rivers, and the seasonal melting of ice. A prominent feature in the surface water is the oceanic polar front, which separates the cold, less saline surface water of the Arctic Ocean from saltier warmer water originating in the oceans farther south. Arctic surface water is less salty than deep ocean water and the surface waters of other oceans because of meltwater from ice as well as large inputs of fresh water from north-flowing rivers. The fresher water floats on top of more saline water, and the water mass has distinct layers with different temperatures (*thermocline*) and salinities (*halocline*). The halocline that separates the fresher from the saltier water creates a lid that keeps deeper, warm water from reaching the surface.

About one-third of the Arctic Ocean is covered by *continental shelves*, the widest of any ocean. The central part of the Arctic Ocean is occupied by two basins: the Eurasian to the east and the Canadian to the west. They are separated by the Lomonosov Ridge, extending due north from Greenland. Both basins contain spreading centres where new material comes up to form new land that are extensions of the North Atlantic ridge system.

The drift of water and ice in the Arctic Ocean moves in a clockwise gyre driven by the polar easterly winds. The gyre is centred over the Canadian basin, not over the North Pole. The ice moves at approximately two miles per day, or one-tenth of a knot. The sea ice in the ocean is in constant motion, following the major currents and growing in thickness as it moves. The trip from one end of the Arctic Ocean basin to the other can take up to six years. Stresses from winds, upwelling, and water currents lead to patches of open water year-round called *polynyas*. They serve as important gathering grounds for marine wildlife and hunters.

Earth Sciences

Earth systems sciences study the processes that create the canvas upon which the atmosphere, oceans, and living organisms can exist. The Earth is the source of all elements, excluding the occasional extraterrestrial input from meteors and the solar wind. The position of the Earth in the solar system and the internal energy of the Earth that initiates its rotation causes the seasons that are an essential part of the Arctic. The Earth system is the driver of evolution over geological time, causing oceans and continents to shift, affecting climates and long-term biological evolution strategies. The availability and interaction of these elements on multiple scales has both direct and indirect influences on individual organisms and environmental systems. Understanding the sources, sinks, transformations, and fluxes of these essential elements above and below surface is critical. For instance, large stands of forest act as a carbon sink, storing huge amounts of carbon in the trees and soil. Removal of this storage capacity would force other reservoirs in the carbon cycle, such as the atmosphere or ocean, to increase carbon levels.

The Earth is believed to be 4.6 billion years old and has been changing constantly throughout its lifetime. The Earth has a solid inner core composed primarily of iron and nickel and a liquid outer core with similar composition but lower temperature and pressure. The mantle surrounds the outer core and makes up about 70% of the volume of the Earth. Variations in temperature create changes in density, in turn causing currents of moving material. The upper part of the mantle is referred to as the *asthenosphere*. Circulation cells in the asthenosphere drive *plate tectonics* by moving the uppermost part of the mantle and crust (*lithosphere*).

The processes on Earth—such as the movement of tectonic plates, precession of Earth's axis in space, volcanic activity, and mountain formation—occur on time scales that are almost imperceptible to one human lifetime. Earth scientists consider *gradual change* to occur over long periods of geological time, millions to billions of years. *Catastrophic change* is considered to be that which takes place instantly (seconds) or rapidly in geological time (centuries). It is these large events like volcanic eruptions or earthquakes that indicate activity that underlies the presence of all processes on Earth.

Two key sources of energy fuel the Earth system. External energy comes from solar radiation. Because the Earth is tilted at 23.5^{o}, the amount of radiation received at a particular latitude varies during the course of the year creating the seasons. Internal energy is left over from Earth's formation and is a product of radioactive decay that heats the inside of the Earth. It is this internal energy that drives volcanism and mountain formation and the constant changing of the Earth's landscape.

The Arctic topography is as varied as the processes that created it. Old crystalline shields underlie most of eastern Canada, Greenland, and Fennoscandia. Younger sedimentary rock, eroded into plains, cover large parts of Russia and the Mackenzie River Valley in Canada. Sedimentary rock has folded into mountain chains in the Ural Mountains, Alaska, and Yukon Territory of Canada. A similar process forms the mountain ranges of the northern Canadian Arctic Archipelago, while Iceland and the Aleutian islands are of volcanic origin. The history of the formation of the Earth helps to describe how the Arctic was marked with these features.

Plate tectonics is the theory that the Earth's crust is constantly in motion, rearranging the structure of the semi-rigid lithosphere over the soft, malleable asthenosphere. The theory of plate tectonics explains the origin and distribution of earthquakes, mid-ocean ridges, deep-ocean trenches, mountain chains, and volcanoes. It also explains the drift of continents and why the distribution of land changes with time. Three times over the past billion years, supercontinents (a stage where all the continents form one massive continent, such as Pangaea) have existed.

New material comes up from the mantle to the surface of the Earth through mid-ocean ridges and volcanoes. Volcanic eruptions can either be violent explosions or slow-moving lava flows. Eruptions can occur in the air, under water, or under glaciers. Iceland is one of the few places on Earth where mid-ocean ridge volcanism has built a mound of basalt that juts from the sea as an island. Iceland straddles two crustal plates; and they are being pushed away from one another by the new material coming up through the mid-ocean ridge. As a result, Iceland is being stretched apart, with faults forming as a consequence.

Volcanic eruptions produce large quantities of ash, sulphur dioxide, and carbon dioxide. Fine dust and aerosols enter the stratosphere, the upper layer of the atmosphere. It takes about two weeks for the material to circle the planet. Particles stay suspended in the atmosphere for months to years because they are above the weather and do not get washed away by rainfall. The haze the particles produce causes cooler average temperatures because the haze absorbs incoming visible solar radiation but does not absorb the infrared radiation that rises from the Earth's surface and flows out to space.

Earthquakes are a feature of plate tectonics that are most prominent in *subduction zones*, regions where crustal material is being pushed back into the mantle. The coastal regions of the entire North Pacific basin are subduction zones that are subject to violent earthquakes and occasional volcanic activity. Alaska, western Canada, and Subarctic Japan regularly experience earthquake activity. *Tsunamis* are also a threat in the North Pacific region. Tsunamis are produced by submarine earthquakes or volcanic eruptions. They may travel across the ocean for thousands of miles without being noticed. They build up to great heights over shallow water at the shore. Tsunamis have the potential to destroy entire coastal communities.

The changes that take place on Earth reflect complex interactions between geological, chemical, and biological phenomena. For example, plants affect the composition of the atmosphere by providing oxygen; atmospheric composition, in turn, determines the nature of chemical weathering in rocks. Some scientists suggest that the Earth system is analogous to a complex living entity. The *Gaia hypothesis* views the Earth as a complex system involving the biosphere, atmosphere, oceans, and soil. The hypothesis proposes that our planet functions as a single organism that maintains homeostasis and all conditions necessary for its survival. The totality of all parts results in a *feedback system* that tries to maintain an optimal physical and chemical environment for life on planet Earth. Some scientists, however, view the Gaia hypothesis as a creative characterization of phenomena that the scientific community inherently accepts within the principles that are used to study the Earth and its processes. Such scientists assert that scientific concepts such as equilibrium, homeostasis, and the laws of thermodynamics require that the Earth exist as its own self-correcting mechanism.

Some kinds of global changes on Earth are owing to changes in the proportions of chemicals held in different reservoirs through time. The *biogeochemical cycle* involves non-living reservoirs like the atmosphere, the crust, and the ocean; and living reservoirs such as plants, animals, and microbes. Biogeochemical cycles attain a steady-state condition in which the proportions of a chemical in different reservoirs remain fairly constant in the geological short term, even though there is a constant flow of the chemical between reservoirs. The most important biogeochemical cycles are the *hydrological cycle*, the *carbon cycle*, the *nitrogen cycle*, and the *phosphorus cycle*. (The carbon, nitrogen, and phosphorus cycle is discussed in the next section, "Ecosystem Sciences.")

The hydrological cycle is the overall circulation of water from reservoir to reservoir in the Earth system. Most of the hydrological cycle occurs between the oceans and the atmosphere. The largest reservoir is the ocean, which covers

71% of the Earth's surface and, with sea ice, houses 97% of the Earth's water supply. The hydrological cycle begins when water evaporates from the ocean and enters the atmosphere. Atmospheric water slowly condenses and forms clouds that release rain or snow onto the oceans or land. The water that falls on land may be held in glacial ice or in surface water like lakes, rivers, or bogs. Some water flows back to the ocean, some evaporates into the air, and some sinks into the ground. The water that sinks deeper into the ground may be trapped for a while as *groundwater*.

Groundwater fills the holes and cracks between grains of sediment in the ground. Groundwater flows slowly; some of it bubbles back to the ground surface or into the bed of lakes, rivers, or streams. Some groundwater flows all the way back to the coast and reaches the sea. Some water becomes part of living organisms and returns to the atmosphere by *transpiration* from plants or *respiration* by animals.

Water that has come down as precipitation and has not been allowed to melt becomes *glaciers*. Glaciers are rivers or sheets of ice that last all year and flow slowly, carving the landscape and depositing large quantities of sediment. Glaciers exist in Alaska and western Canada, and they cover most of Greenland and Antarctica. *Alpine* glaciers primarily form in, or adjacent to, mountain regions. *Continental glaciers*, or ice sheets, are vast layers of ice that spread over thousands of square kilometres of continental crust. They flow outwards from their thickest point; and they thin towards the margins. The upper part of the ice sheet is brittle and may crack to form crevasses. Large ice sheets cause the lithosphere to sink. As the ice sheet melts, it causes glacial rebound over thousands of years. Some of the land is still rebounding after being pressed down by the weight of the ice sheets during the last glaciation. Around Hudson Bay in Canada, for example, the land rises at a rate of one metre per century. In the circumpolar North, ice sheets are presently found only on Greenland, but they covered extensive areas of the Earth when the climate was cooler. Should any of Greenland's ice sheet melt, it would contribute significantly to the rise of the global sea level.

The landscape of the circumpolar North has been shaped by repeated glacial cycles over geological time. In the North American and western Eurasian Arctic, ice sheets have scoured the landscape, tearing away topsoil. In areas with hard granite bedrock, the glaciers left the land dotted with depressions that became lakes filled with fresh water, or fjords filled with sea water. In other areas, the glaciers piled extensive moraines and sedimentary deposits on top of bedrock.

In the Arctic landscape, *tundra*—a treeless region supporting only low shrubs, moss, and lichen capable of living on permafrost—dominate the landscape. The *permafrost* layer, which is ground that freezes in the winter and thaws in the summer, governs the fate of water in the Far North. Only a thin top layer, called the active layer, thaws each summer. The active layer ranges between a few centimetres in the northernmost wet meadows to a few metres in warmer, drier areas. As the active layer refreezes, the ground contracts and splits into pentagon shapes. Water fills the gaps between the cracks and freezes to create wedge-shaped walls of ice. Along the northern coasts, frozen ground meets the sea and extends under some continental shelf seas.

Groundwater formation is much slower in frozen ground than unfrozen ground. The groundwater can be on top of, in cracks within, or underneath the permafrost layer. In spring, permafrost contributes to flooding. The two to three weeks of snowmelt in the spring account for 80–90% of the freshwater input to the land. Instead of seeping into the ground, the meltwater flows over the frozen surface into rivers, lakes, and wetlands. The lack of waterlogged soil in wetlands delays the decomposition of plant matter and results in a buildup of organic materials, such as peat. Because the ground has such a limited ability to store water, the spring flood can be violent, undercutting riverbanks and causing extensive erosion along its path. Ice jams add to the uneven flow and erosion. The rivers can thus carry huge amounts of sediments that are deposited along their course and in wide deltas.

Permafrost presents a unique challenge to people who live in the Arctic or who work to extract resources from these regions. For example, heat from a building may warm and melt underlying permafrost, creating a bog into which the building settles and breaks apart. Buildings in permafrost regions must be placed on stilts, so that cold air can circulate beneath them to keep the ground frozen. Tundra presents other challenges because it is extremely sensitive to disturbance and recovery after disturbance can take hundreds of years.

Ecosystem Sciences

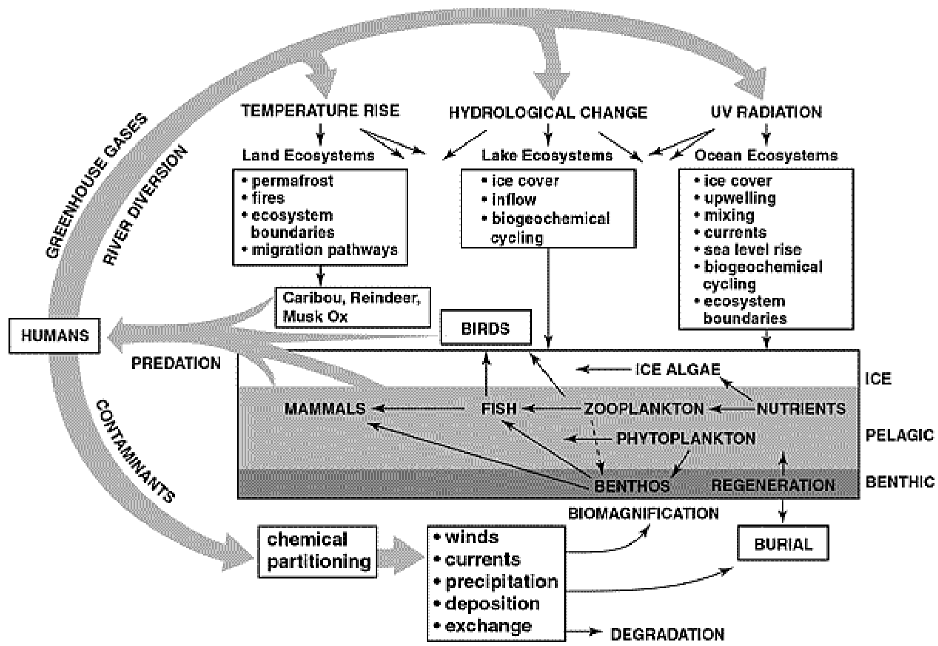
The ecosystem sciences study the processes that affect living organisms. They use chemistry, physics, biology, botany, and soil science to understand the complex interaction among living organisms and between living organisms and biogeochemical cycles. As discussed above, the hydrological cycle is the most important cycle because water is essential to living organisms. The hydrological cycle is distinct from other biogeochemical cycles in that most cycling occurs in a physical form, whereas the nutrient cycling of carbon, nitrogen, and phosphorus involves chemical cycling. The movement of water within and between ecosystems allows the transfer of material in several other biogeochemical cycles.

The carbon cycle is important because carbon is a basic constituent of all organic compounds. Most carbon in the near-surface realm of Earth originally bubbled out of the mantle in the form of carbon dioxide gas released from volcanoes. Once it enters the atmosphere, it can be removed by dissolving in sea water, or absorbed by photosynthetic organisms that convert it to sugar, allowing it to enter the food chain. Some carbon returns directly to the atmosphere by the respiration of animals, by agriculture flatulence, or by decay of dead organisms. The reciprocal processes of *photosynthesis* and *cellular respiration* provide a link between the atmosphere and terrestrial environments. Carbon that does not return directly to the atmosphere can be stored for long periods of time in fossil fuels (oil or coal) or in limestone. This carbon either returns to the atmosphere in the form of carbon dioxide as a result of the burning of fossil fuel or returns to the sea after being dissolved in river or groundwater. The concentration of carbon dioxide in the atmosphere plays an essential role in controlling Earth's climate because an increase in carbon dioxide concentration warms the atmosphere, while a decrease cools it down.

Nitrogen is another key element in ecosystems because amino acids in the proteins of organisms require nitrogen. There are two pathways in which nitrogen can enter the ecosystem: *atmospheric deposition* and *nitrogen fixation*. Through atmospheric deposition, the nitrogen minerals ammonium (NH_4^+) and nitrate (NO_3^-) are added to the soil by being dissolved in rain. Nitrogen fixation is the process by which single-celled organisms called prokaryotes convert a nitrogen molecule (N_2) into minerals that can be used to synthesize organic compounds such as amino acids. The product of nitrogen fixation is ammonia (NH_3). Ammonia is a gas that can be released back into the atmosphere. Animals assimilate nitrogen compounds by eating plants or other animals. Although nitrogen exchanges between soil and atmosphere are significant over the long term, the majority of nitrogen in ecosystems is recycled locally by decomposition and re-assimilation.

The phosphorus cycle is simpler than either the carbon or nitrogen cycles. Phosphorus cycling does not include movement through the atmosphere. There is only one form of phosphorus that plants can absorb and use for organic synthesis: phosphate (PO_4^{3-}). The weathering of rocks gradually adds phosphate to the soil. After animals assimilate phosphorus by eating plants, it is added back to the soil by the excretion of phosphate by animals and by bacterial and fungal decomposers. While phosphorus cycling tends to remain localized, it can leach into the water table and drain from terrestrial ecosystems to the sea. Phosphate that reaches the ocean gradually accumulates in sediments and becomes incorporated into rocks that return to the terrestrial environment through geological processes that raise the sea floor.

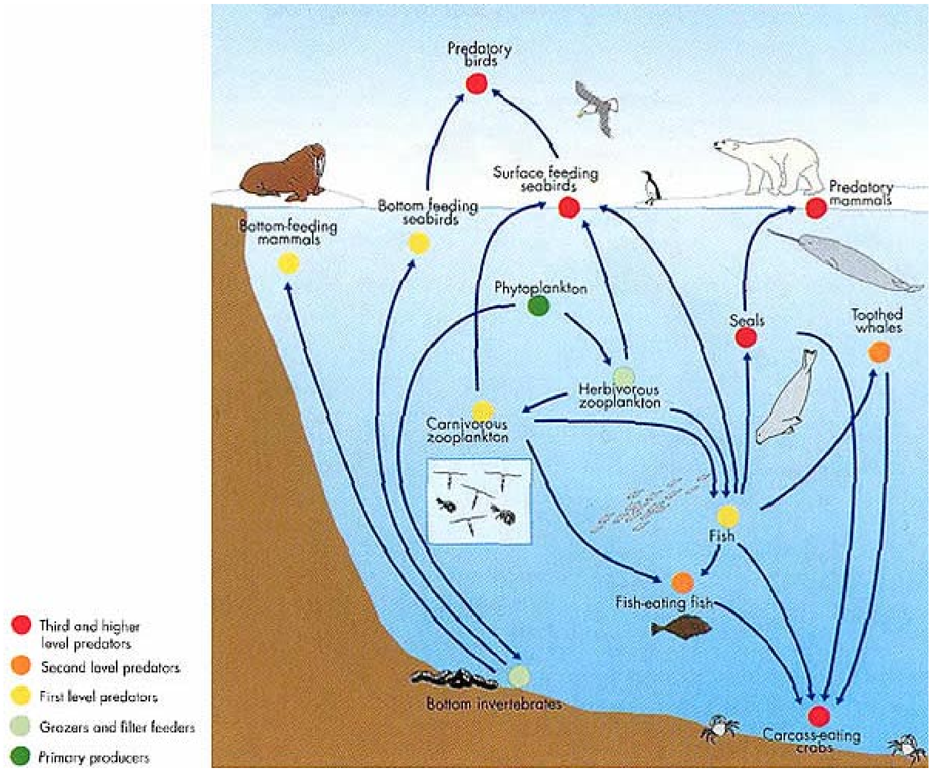
Figure 1.3 illustrates the complex interactions between the components of the Arctic ecosystem. The biogeochemical cycles described above interact with living organisms, the Sun, and regional and global ecosystems.



Source: AMAP (2002)

Fig. 1.3 An illustration of the complex relationship of Arctic ecosystem components

The cool temperatures and short summers of the circumpolar North have required successful living organisms to acquire adaptive strategies that favour life in the Arctic and Subarctic. There are many relationships between species in the Arctic, primarily centred on feeding relationships. The species in an ecosystem are divided into *trophic levels* on the basis of their main source of nutrition. The pathway along which food is transferred from trophic level to trophic level is known as a *food chain*. The comprehensive components of a food chain are as follows: primary producers; primary consumers; secondary consumers; tertiary consumers; and quaternary consumers. A food chain is a simplification of the actual relationships, but it allows ecologists to understand the flow of energy and nutrients through the trophic levels of an ecosystem. A *food web* represents the complex feeding relationships that actually occur in an ecosystem. For instance, humans do not eat only animals, as the hierarchy of a food chain would suggest; we also eat plants. (See fig. 1.4.)



Source: CAFF (2001)

Fig. 1.4 Simplified Arctic marine food web

At the most basic level, *primary producers* synthesize sugars and other organic compounds from sunlight. Photosynthesis, as this process is known, is the most basic organic process that supports all others in an ecosystem. Primary producers include plants in the terrestrial environment and phytoplankton in the marine environment. *Primary consumers* eat plants and algae and include herbivores in the terrestrial environment and zooplankton in the marine environment. In the marine environment, primary consumers are also known as grazers and filter feeders. *Secondary consumers* are carnivores that eat herbivores. A mouse is an example of a secondary consumer in the terrestrial environment. In the marine environment, secondary consumers are also called first-level predators and include carnivorous zooplankton and bottom-feeding mammals. *Tertiary consumers* are carnivores that eat carnivores. A snake that eats a mouse is an example of a tertiary consumer in the terrestrial environment. In the marine environment, tertiary consumers are called secondary predators and include fish-eating fish and toothed whales, such as baleen whales. Some ecosystems have one more trophic level called *quaternary consumers* in the terrestrial environment and third-level predators in the marine environment. On land, quaternary consumers include hawks and owls. In the marine environment third-level predators include polar bears and orcas.

All organisms require energy for growth, maintenance, reproduction, and locomotion. The extent of the photosynthetic activity of the primary producers sets the spending limit for the energy budget of the entire ecosystem. The amount of light energy converted to chemical energy by the primary producers is called *primary productivity*. Different ecosystems vary considerably in their productivity. Tropical rain forests are the most productive ecosystems. Estuaries and coral reefs also have high productivity; however, the open ocean contributes more primary productivity than any other ecosystem. In the Arctic, tundra and non-estuarian areas of the marine environment have low productivity. The semi-enclosed water bodies in the Arctic, such as fjords and bays, house estuarine environments that are important links between the terrestrial environment and the oceans because they act as sediment traps. These environments are much more biologically productive relative to the other areas of the Arctic. As a result, ships that make port in bays or travel through semi-enclosed waterways are a particular concern as evidenced by the Exxon Valdez oil spill off the Alaska coast.

Most biochemical processes are temperature-dependent, and the rate of biological activity slows down at temperatures below a certain level. As a result, many plants and animals in the Arctic grow more slowly than they would elsewhere. Low temperatures also limit the chemical weathering of bedrock, a process that supplies nutrient ions to the soil. Slow weathering rates can be compounded by permafrost. Particularly in the tundra regions, the living and non-living components of the environment are slow to recover from physical destruction connected with resource extraction.

Reduced microbial activity also limits the rate at which nutrients can cycle in the Arctic ecosystem. Carbon accumulates in the soils, and many nutrients remain bound and unavailable. It is this accumulation of carbon, however, that makes the Arctic regions so valuable for natural resource extraction, particularly fossil fuels. The slow degradation processes lead to deficiencies in many key nutrients in both terrestrial and lake ecosystems. Plant growth is often limited by lack of nitrogen and phosphorus, along with low temperatures. Because the growing season in the Arctic is short, plants that store nutrients are favoured.

Algae blooms represent a form of ocean ecosystem destruction: loss of biological productivity. Algae blooms are caused by microscopic, single-celled plants that exhibit periodic population explosions along coastlines throughout the world. Several types of algae are toxic and shellfish feeding on the single-celled plants can accumulate toxins, posing a threat to human health. The blooms are often referred to as “red tides” and are associated with the death of marine mammals, fish, and seabirds and with the formation of “dead zones” where the productivity of coastal marine ecosystems collapses because of an oxygen deficiency.

Large regions of the circumpolar North, primarily in the Subarctic, are home to large stands of boreal forests. Forests house a tremendously productive ecosystem that is capable of supporting large numbers of living organisms from mammals high on the food chain, such as bears, to simple microbes. Forests are important in the global context because they store carbon and transpire oxygen, continually adding oxygen to the atmosphere. The loss of large stands of trees causes other elements stored in the forest ecosystem to be lost from that system. Typically, when a tree dies, the nutrients that were housed in the tree are returned to the soil and then taken up into another living organism. When large stands of trees are removed from a region, the nutrients are not returned to the soil and are lost from the boreal ecosystem, sometimes requiring hundreds of years before they are replenished. Removal of large sections of the forest near coastlines causes runoff that limits productivity in coastal marine regions.

Wildlife biologists use their understanding of population dynamics to manage caribou, reindeer, migrating birds, and bears. As with the human community, within each biological community there is a role, or *niche*, for all members in that community. As scientists understand these roles, they begin to learn the external and internal factors that both limit and maintain population growth. *Density* and *dispersion* are two important characteristics of any population. Density is the number of individuals per unit area or volume. Dispersion is the pattern of spacing among individuals within the geographical boundaries of the population. The factors that influence the distribution of a species over its range are the subject of biogeography. The *carrying capacity* is the maximum population that can be supported by a given region. The critical number, or critical threshold, is the number below which a population cannot sustain itself and continue to reproduce. Information about population dynamics is especially relevant in the circumpolar North because the inhabitants of the region depend on the resources for both sustenance and income. In addition, the changes in key species can indicate to scientists larger changes that may not have been observed throughout the Arctic.

Predation is the pathway by which contaminants move from animal to animal in Arctic food webs (AMAP report). Energy is important for survival in cold environments, and Arctic animals have adapted through a preference for high-energy, fatty foods. As a result, Arctic animals are especially vulnerable to fat-soluble contaminants like PCBs and some POPs, which migrate up from other regions of the world.

Student Activity

1. Interview an older member of your community to find out how weather patterns in the area have changed over time and how people's lives have been affected by the change.

2. If you live near the sea, interview an older member of your community to determine changes in distribution and characteristics of sea ice and how these changes have affected subsistence hunting and fishing.
3. Do you see evidence of permafrost in your area? Has it been necessary for your community to address the problems caused by permafrost?
4. Choose an example of wildlife in your area (bird, fish, mammal) and construct its food web, indicating at least five other examples of wildlife that are included in its web.

Part III: Arctic Issues and Biocomplexity

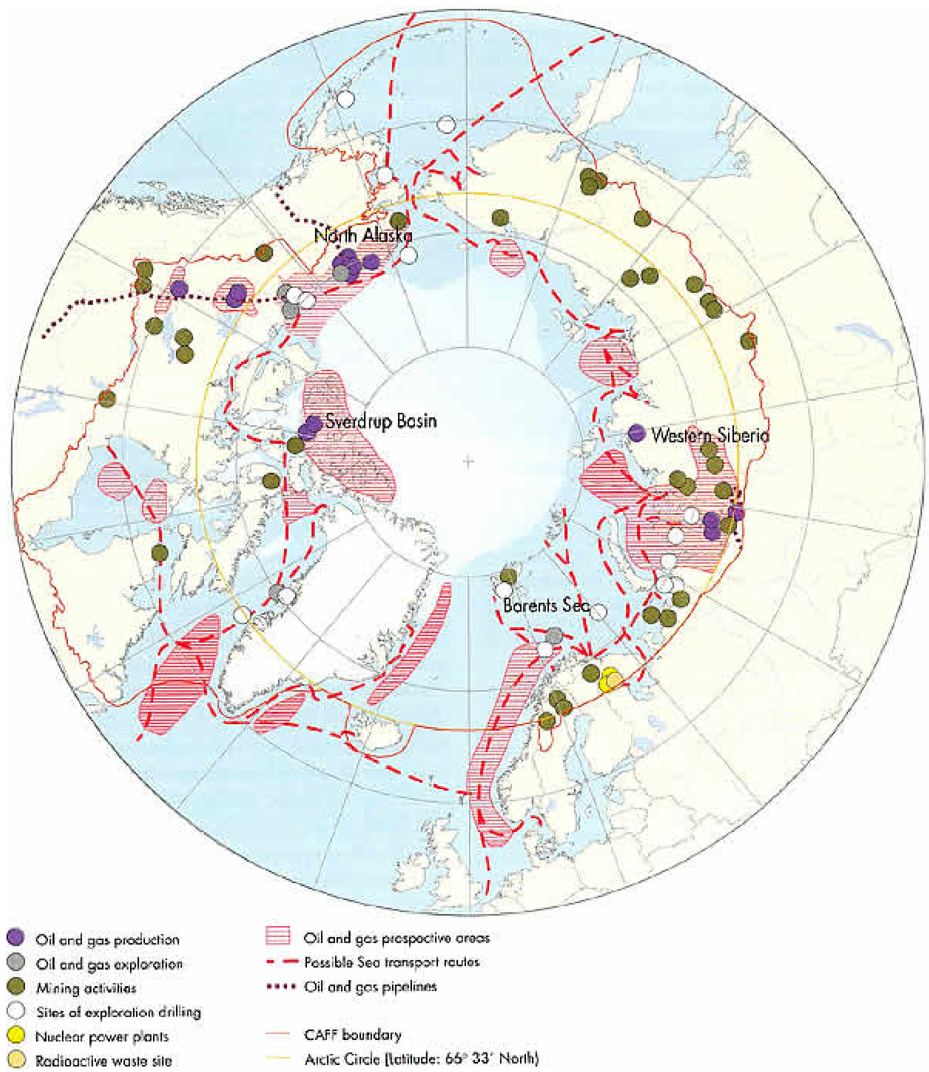
The biocomplexity of the Arctic is integrally linked to the global ecosystem. A discussion of the future of the planet is not complete without including the Arctic. Paradoxically, the complex interactions of the Arctic ecosystem are not completely understood. The Arctic reacts to changes in ways that have not been observed in other regional ecosystems on Earth. As explained in the Overview of this module, being a cold-climate ecosystem the Arctic is characteristically fragile, sensitive to disturbance, and susceptible to toxic accumulation. As a result, the Arctic is vulnerable to human activities.

Science and Policy

The biocomplexity of the Arctic must be understood in terms of both science and management. A fundamental challenge for science is to understand human dependence on natural systems and to determine the economic and social impacts of this dependence. How does the interaction of human and natural processes affect the capacity of natural systems to meet human resource needs and to support the quality of life? Achieving sustainability will allow Arctic residents to maintain the integrity of the Arctic ecosystem.

There are several issues that are specifically related to sustainability in the Arctic because of its unique vulnerability: resource depletion and ecological contamination. The Arctic is especially vulnerable to resource depletion because many industries currently look to the Arctic as a source of raw materials. Figure 1.5 shows industrial activities and oil and gas reserves in the Arctic. Because of the relatively short history of industrialization in the Arctic, resources have not been extracted to the degree that has occurred in other parts of the world. As a result, the Arctic is a prime target for timber, carbon resources like coal, oil and natural gas, and marine-based food for raw materials to support the increased industrialization in other areas of the world. Many of the locations for oil and gas extraction are on sensitive tundra lands where the benefits are constantly assessed against the risks of ecological damage.

The sensitivity of the Arctic ecosystem makes the threat of ecological contamination especially dangerous because of the unknown consequences. Contaminants are a threat to the Arctic region because the cooler regions of the poles tend to accumulate contaminants from lower latitudes, with no mechanism to transport the contaminants to another region. Although the Arctic is still viewed as a relatively clean region of the globe, heavy metals, radioactive nuclides, and persistent organic pollutants from more than 7,000 kilometres away have been found in the region. Even small amounts of pollutants in subsistence diets can have a magnified effect by carrying on to offspring. The impact of environmental degradation on human health is the most urgent issue requiring the effective uses of science to improve the conditions of life. Natural resource managers work to facilitate a sustainable balance between the environment and human needs. Co-management strategies are increasingly important to monitor the effects of resource extraction and ecological contamination of biological resources like anadromous fish, migrating birds, and marine mammals.



Source: CAFF (2001)

Fig. 1.5 Industrial activities and oil and gas reserves in the Arctic

The Amchitka Case[1]

The history of the Aleut region has been controversial with respect to environmental policy and the civil rights of Alaska's indigenous people. These events have produced obstacles to trust in the government's stewardship of the region that only diligent regard for stakeholder participation in its future management can overcome. Management must be based on sound knowledge of the biological and physical characteristics of the natural system and the hazardous materials that have been deposited within. A wide variety of

[1] The authors wish to acknowledge the contribution of Lawrence K. Duffy and Stanley Wright to the Amchitka discussion.

outcomes from improper management is possible, including death and population decline among marine organisms, leading to disruption of food chains and the elimination of sensitive species.

While many contaminants come to the Arctic from the far reaches of the globe, Cold War activities caused a legacy of biological resource depletion, ecological contamination, and cultural distrust. During the Cold War, the use of the Arctic as a military arena put incredible stresses on the Arctic ecosystem. Activities of both the Soviet and US military caused unprecedented ecological contamination that resulted in the depletion of biological resources, such as marine mammals, birds, and fish populations. In Alaska, Amchitka Island was the location of several nuclear tests. Many of the documents from the Amchitka tests were classified. Consequently, ongoing assessments of the ecological health of the region and potential human health damage have not been performed. Without basic scientific analysis, quantifying sustainability and preparation of a management plan for long-term stewardship have been limited in the Amchitka region.

Amchitka Island is situated in the mid-Aleutians in the North Pacific Ocean. The island was the site for three nuclear underground test shots. Many concerns over earthquakes, pollution, and marine resources were voiced at the time of the testing. Initial surveys did not report evidence of radioactive contamination in the marine environment, and residual radionuclides were considered confined to the test cavities. Retention of radionuclides in the glass breccia formed by the explosions, and the few kilometres of faulted and fractured rock that separates the shot cavities from the ocean, function as barriers to release. There is concern regarding the future transfer of radionuclides to the sea, to marine ecosystems, to sensitive or endangered species, to foods harvested by Aleut fishers, and to seafood of commercial interest. For a successful long-term stewardship program on Amchitka, plans for the scope and frequency of monitoring for these concerns is needed.

People, History, and Geography

Amchitka Island is unique because it is situated at the confluence of many different complex systems. Amchitka is in a remote location with protected status as a national wildlife refuge with endangered species. It is a part of the marine environment that supports the subsistence lifestyle of indigenous peoples and significant international, commercial fisheries. Amchitka exhibits ocean/island hydrology and is located within an actively deforming plate boundary characterized by intense earthquake activity.

The Aleut people have traditionally lived on the Alaska Peninsula and on the islands of the Aleutian chain. Evidence indicates that Aleuts have lived continuously in the Aleutians for more than 6,000 years. At various times during the Holocene—the last 10,000 years—Amchitka has supported a substantial human population of perhaps 1,000 people. When Danish sea captain Vitus Bering arrived in the Aleutians in 1741, he found all habitable islands occupied. With Russian colonization of the Aleutians, the Aleut populations fell precipitously because of disease and rapid depletion of resources, including the near-extinction of sea otters.

The region was purchased by the United States in 1867 and eventually some protection of fur-bearing animals was put in place. At the onset of the Second World War, the island contained only an abandoned Aleut village. This was destroyed by US forces so that it would not fall into enemy hands. Inhabited Aleut villages of the region were also intentionally destroyed and their residents removed to camps in southeast Alaska. Non-indigenous civilian residents were allowed to remain in the region during the war years. Some villages have since been re-established. While none are in the immediate vicinity of Amchitka, the Aleuts and the world at large derive food from the surrounding seas. The Aleuts view this region as both their historic home and home for the future.

In the context of the biologically rich Aleutians, Amchitka Island stands out as an especially important part of the ecosystem. Its unusual expanse of gently rolling maritime tundra dotted with freshwater lakes contrasts with the sea cliffs and desolate volcanic landscapes of many of the islands. Amchitka supports a dense bird population with a diversity of species, some of which are shared with Asia and some with North America. Similarly, its extensive intertidal zone served as a haven that permitted the survival of sea otters in the face of plundering during the eighteenth and nineteenth centuries. It will continue to serve a similar role for otters and other marine mammals during the times of population stress in the future. Primary productivity, measured in grams of carbon fixed per square metre per year, is extremely high in the Bering Sea and along the Aleutian chain. The marine food web at Amchitka and neighbouring islands is rich and diverse and supports migratory seabirds, marine mammals, and pelagic fish. This productive food web can support extensive subsistence and commercial fisheries.

Amchitka Island is a currently uninhabited portion of the Aleutian archipelago, which stretches from the tip of the Alaska Peninsula to the Kamchatka Peninsula of Russia. Amchitka is part of the Alaska Maritime National Wildlife Refuge, which was established in 1913 to allow the use of the islands for military activities as needed. The island served as a military base that opposed the Japanese occupation of neighbouring Kiska Island during the Second World War. The three major underground nuclear tests conducted during the Cold War era were Long Shot in 1965 (80 kiloton); Milrow in 1969 (1 megaton); and Cannikin in 1971 (5 megatons). Intense public opposition to testing drew attention to the dangers of pollution and destruction of valuable marine resources, particularly prior to Cannikin. There was also deep concern that earthquakes may open the shot cavities, allowing leakage of radioactive material.

The western Aleutian region, where the North Pacific plate subducts obliquely beneath North America at 7–8 cm/year, is one of the most volcanically and seismically active regions of the world. It was because of this high seismicity that Amchitka was selected for the first nuclear test, Long Shot. The objective was to determine whether a nation wishing to clandestinely develop nuclear weapons could hide a nuclear explosion within intense natural seismicity. The Milrow test was conducted to determine whether the island could withstand a large explosion. Such explosions (1 megaton) had been deemed too large for the Nevada Test Site because of ground motion concerns in Las Vegas. Since Amchitka seemed to withstand the Milrow test, a Spartan missile of the Safeguard Ballistic Missile Defense Program (Cannikan) was tested. Vigorous opposition by the Aleut and environmentalist communities and formal protests from the governments of Japan and Canada were reported. As a result of the Cannikin test, approximately one metre of uplift occurred along the adjacent Bering Sea coast, resulting in a permanent reduction in area available to most littoral species.

Nature of the Problem

Large quantities of radionuclides have been sequestered in the three test shot cavities. There is uncertainty regarding the potential for radionuclides to be mobilized and enter the marine and atmospheric environment. Marine contamination and health risks remain uncertain. This is partly because the data regarding the radionuclides at the source was classified. Virtually no data have been acquired regarding the subsurface of the Amchitka site or the surrounding ocean over the past two decades. In addition, the amount of reliance of indigenous Aleut communities on Amchitka waters needs to be determined. Future use is expected to increase as long as no radionuclides are detectable.

Despite the presence of hazardous substances or conditions, organisms are not at risk if there is no exposure pathway. Measuring radionuclide levels in individual organisms will greatly reduce uncertainty at Amchitka. Geological and oceanographic measurements will reduce uncertainties that influence fate and transport of radionuclides and other contaminants.

In a complex system, a variety of pathways exist from the environmental media (water, soil/sediment, air, and food) through the uptake pathways (direct dermal or membrane contact, ingestion, inhalation, or injection). For Amchitka, these are illustrated in table 1.1. The airborne pathway would deliver released radionuclides to other sites.

Table 1.1 Exposure matrix for the marine ecosystem and human consumers at Amchitka (derived from Gochfeld)

	Water	**Soil/Sediment**	**Food**	**Air**[b]
Direct Contact	*Invertebrates, Aquatic vertebrates*	*Benthic organisms*	Not applicable in general	Airborne deposition on exposed organisms
Ingestion	*Invertebrates, Fish, Seabirds*[a]	*Benthic organisms, some terrestrial organisms*	*All organisms in food chain including humans*	Airborne deposition on exposed food items
Inhalation	Some aerosolization from ocean surface and surge zone	Inhalation of dust carried by winds	Not applicable in general	All air-breathing organisms

Notes: Major pathways are shown in italics. Airborne deposition is a potential confounding source of radionuclides.

[a] seabirds are capable of drinking sea water and excreting the salt

[b] historic airborne transport of "fallout" from nuclear tests and nuclear accidents would have delivered radionuclides to Amchitka and its marine ecosystems. This is a potential confounder for exposure to test shot radionuclides.

Sustainability and Long-Term Stewardship

The Amchitka case is an illustration of how important sustainability is to developing long-term stewardship in the Arctic environment. The Amchitka littoral zone and surrounding seas are known for their cultural traditions and ecological importance. The Aleut people have long used them for subsistence fishing; but since the nuclear test era, these regions have become a major international fishery. In order to sustain the area and manage it for the long term, thorough research of current conditions and the possible damage from nuclear tests would be necessary. It is known that the inventory of radioactive material deposited in the shot cavities is significant. It is plausible that disturbances in the physical environment could create fractures that connect the shot cavities to the marine environment. Some fractures may exist now, while others may be caused by future earthquake activity. If hazardous material reaches humans, it will have started as the contents of a shot cavity. Contaminants would enter the groundwater system as a solute or colloidal suspension. The contaminated groundwater could leak into the ocean, becoming incorporated into the marine food chain. Human consumption of marine animals would therefore act as a contaminant pathway.

A state-of-the-art knowledge base does not exist for the Amchitka area from which to assess the hazards and risks or move forward to long-term stewardship. Except for surveys conducted immediately after each nuclear test, no systematic effort has been made at Amchitka to detect leakage of contaminated groundwater into the marine environment. Without a sound basis in empirical observation, plans for stewardship of the site will lack credibility. In turn, people who depend on this region for subsistence or commercial fishing will not be satisfied with safety of the marine resource.

A stewardship plan for Amchitka should include both baseline and monitoring studies. First, studies need to identify the current levels of radionuclides in the marine environment and food web. It is especially important to study those species that could contribute to high radiation doses in higher predators in the food chain, including humans. Second, the current contents of the Amchitka shot cavities must be identified and distinguished from other sources of radionuclides. Third, the condition of the rock envelope that is the barrier between radioactive material and the ocean must be evaluated. Finally, pathways for transfer, accumulation, and attenuation of radionuclide concentrations must be assessed.

A stewardship and monitoring plan should include two primary goals: (1) confirmation of safety or warning of risk should be executed for all levels of the marine food chain, including humans; (2) a proper evaluation of the physical environment should allow efficient, targeted sampling for radionuclide contamination. Such a strategy would reduce the uncertainty in determining the rate, magnitude, and risks associated with potential future radionuclide leakage.

Amchitka illustrates the complexity of ecological destruction issues as they relate to the biocomplexity in the Arctic. While the Arctic is a sparsely populated region of the globe, destruction of components of its ecosystem has a direct effect on the livelihood of cultures that depend on subsistence. There also exists the possibility that radionuclide contamination of the entire North Pacific region will indirectly affect the global ecosystem.

Student Activity

Identify an environmental risk in your area and make a science-based argument to a local decision-maker for a policy that would improve the condition.

Part IV: Guiding Principles for Long-Term Stewardship

Ecological Principles

Many attempts have been made to establish principles of management for long-term stewardship. One approach is to consider the environmental terms from Part I of this Lecture as a framework for organizing a range of ecologically significant ideas. Following is a summary of major principles compiled from recent thinking on land and environment relationships (based on work by Charles Krebs and the Eco-literacy Council in Steel, et al. 2003):

> Ecosystems—*Organisms and environment co-evolve as interactive components of habitat.* Each kind of life is suitable to the physical condition of its habitat, including the soil, moisture, light, and quality of air. The species exists because it can survive with its neighbours in these habitats. All species are dependent on specific types of environments to survive. For instance, polar bears depend on the Arctic ice and cold temperatures.

> Biodiversity—*The health of an ecosystem is maintained through resilience and adaptation.* The key mechanism underlying evolutionary change is natural selection, which occurs over successive generations and accounts for the adaptation and resilience of species. Organisms and species populating the world today derive from species that have changed greatly over time. There are finite limits on how many organisms can be harvested and how much habitat can be destroyed before species survival is jeopardized. The loss of species may adversely affect the balance of ecosystems. Certain species are so important to an ecosystem that their absence indicates environmental imbalance. For instance, should lichens disappear from the Arctic ecosystem, caribou would be deprived of a main source of food and soil would not be properly regenerated from the lichens breaking hard rock into soil nutrients.

> Complex Systems—*Natural systems are self-regulating in response to disturbances.* Ecosystems are capable of recovering form pollution or overexploitation under some circumstances. Ecological communities regulate and organize themselves, maintaining a state of dynamic balance characterized by continual marginal fluctuations. Flexibility, resilience, and oscillations occur in response to disruptions, such as forest fires or disease.

> Biocomplexity—*All living systems nest within other living systems in a vast network of relationships.* Organisms are dynamic and most heavily influenced by their surroundings, including climate. Complex environmental systems include both human and non-human organisms. The members of an ecosystem are interconnected in the vast network of relationships in which all life processes are interdependent and achieve

stability through diverse linkages. Wildlife response to the Exxon Valdez oil spill illustrates the complex interactions of the Arctic ecosystem. All otters, for instance, would have been expected to recover to a similar degree from the disaster; however, while river otters have recovered, sea otters have not because the oil spill directly damaged their immune system and indirectly removed their food supply.

Sustainability—*Natural systems have a recycling mechanism by which living organisms exchange energy and matter with their environments to maintain conditions of stability.* Overexploited or disrupted ecosystems result in different kinds of sustainable regimes, not necessarily in the original stable configurations. Through the constant exchange of energy and matter, ecosystems will always regain conditions of stability, whether the change is in response to a small temperature aberration or a cataclysmic event. Not even a massive disruption such as an asteroid hitting the Earth could alter the eventual return of natural systems to a sustainable configuration.

International Law and the Environment

Growing recognition of the global importance of the ecological principles listed above has resulted generally in greater attention to international law and co-operation as a basis for developing long-term stewardship to secure the environment. Long-term stewardship was clearly outlined in the background report for the 1972 United Nations Conference on the Human Environment (Stockholm Conference). Stewardship is the straightforward idea of management for the sake of another; long-term stewardship is maintaining our planet as a place for life now—and for future generations. An emerging global concern and conscience over the future health of the planet demonstrates the importance of long-term stewardship in our time.

Land and environment issues in the Arctic play a key part in the development of long-term stewardship concepts. The profound effect of (1) global climate change on living conditions and (2) the use of renewable and non-renewable resources as an economic base are the critical factors in a rising political debate over what is to be done to manage the confluence of human and environmental challenges. Management and policy choices regarding human/environment issues are broadly marked by the *conventions* and *practices* that have emerged among states to address increasing concerns over the condition and capabilities of the planet.

International conventions, or treaties, are the foundation and most authoritative source of international law. Next in significance are the *practices* that states follow out of a sense of legal obligation, as if the practice were law. Over time, accepted practices become established as law among nations, known as customary law. Customary law might be thought of as a pool of established practices from which the provisions of international treaties can be drawn. For example, the comprehensive international convention on the law of the sea was a major milestone in regulating the marine environment, but the provisions of the convention basically confirmed existing practices by states, or the customary law.

Although they are the most authoritative source of international law, treaties dealing with environmental matters tend to include few provisions that bind the parties to carry out specific actions. When binding commitments are involved in international environmental agreements (e.g., the Kyoto Protocol requiring developed countries to set binding targets and timetables for the reduction of greenhouse gases), states may be reluctant to become parties to the agreement. The Kyoto Protocol was concluded in 1997, but by 2004, a full seven years later, the agreement had not entered into force because an insufficient number of countries had signed it.

Few international conventions are in place on environmental subjects, and therefore the legal component of an international environmental regime is continually evolving. From the nineteenth century on, treaties regulating environmental matters have been concluded between two countries (bilateral); however, the development of international environmental treaties with many nations as signatories (multilateral) is of more recent origin. One of the earliest multilateral treaties protected biodiversity (the 1911 Convention Respecting Measures for the Preservation and Protection of Fur Seals, concluded by the United States, United Kingdom, Japan, and Russia[2]). One of the most environmentally protective international agreements ever adopted was the 1959 Antarctic Treaty and the 1991 Protocol on Environmental Protection (Hunter, Salzman, and Zaelke 2002, 1061). Although as many as seven countries had territorial claims in Antarctica, the treaty freezes all claims and provides for co-operation on the conservation of living resources and scientific research. A landmark of multilateral co-operation in the circumpolar North was the 1973 Agreement on the Conservation of Polar Bears between Canada, Denmark, Norway, the Soviet Union, and the United States. The majority of multilateral treaties on environmental subjects do not specifically refer to the Arctic, but international environmental treaties tend to have significant implications for the region. Examples of multilateral treaties that are important to land and environment issues are listed in table 1.2, together with the dates that they came into force.

Table 1.2 Multilateral treaties significant to land and environment issues, together with dates the treaties entered into force

[2] The first seal treaty lapsed in 1941 and a new treaty was signed in 1957, which subsequently lapsed in 1988.

Multilateral Treaty	Date Entered into Force
Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space Including the Moon and Other Celestial Bodies (“Outer Space Treaty”)	1967
Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter and 1996 Protocol (London Convention)	1975
Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)	1975
Convention on Wetlands of International Importance Especially As Waterfowl Habitat (Ramsar Convention)	1975
International Convention for the Prevention of Pollution from Ships, as modified by the Protocol of 1978 (MARPOL 78)	1983
Convention on Long-Range Transboundary Air Pollution (LRTAP)	1983
Vienna Convention for the Protection of the Ozone Layer Montreal Protocol 1989 London Amendment 1992 Copenhagen Amendment 1994	1988
International Labor Organization Convention (No. 169) Concerning Indigenous and Tribal Peoples in Independent Countries	1991
Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal	1992
Convention on Biological Diversity	1993
United Nations Convention on the Law of the Sea (UNCLOS)	1994
United Nations Framework Convention on Climate Change (UNFCCC)—Kyoto Protocol [not entered into force as of 2004]	1994
Convention for the Protection of the Marine Environment in the North East Atlantic (OSPAR)	1998
Stockholm Convention on Persistent Organic Pollutants (POPS Convention)	[not entered into force as of 2004]

Bilateral treaties between two countries of the circumpolar eight are numerous and most often are made between countries with common borders. Ecosystems are indivisible so environmental co-operation is unavoidable. To note only two examples, the United States and Canada signed an agreement in 1987 to conserve the Porcupine Caribou herd roaming the countries' common Arctic grounds; and in 1994, the United States and Russia concluded the Agreement on Cooperation in the Prevention of Pollution of the Environment in the Arctic. Neither caribou nor pollution is restricted by land and maritime boundaries.

While international treaties and customary law may be authoritative, they are not yet the most common source of global environmental principles and concepts. Other sources are declarations, statements, diplomatic notes and memoranda, United Nations conferences and resolutions, and the wide variety of governmental and non-governmental initiatives to develop standards of conduct for managing and sustaining the integrity of the environment. Environmental principles achieve status in international law—depending on the extent to which they are consistently practised—and gain consensus among nations.

The underlying assumption in developing international environmental principles, policy, and law is twofold: (1) states are *sovereign* to determine their actions and to conduct on environmental matters (state sovereignty); and (2) states are *responsible* for their actions and for their conduct on environmental matters (state responsibility). Inconsistencies in environmental policies can often be traced to differences in the emphasis that decision-makers give to state sovereignty and to state responsibility. Nonetheless, the two notions of sovereignty and responsibility need to be reconciled if effective legal and political guidelines are to be established for safeguarding the environment.

Because the Charter of the United Nations does not specifically include the environment as an area for international co-operation (Article 1.3), continuous efforts are made to determine international consensus on environmental issues, and to codify those ideas *as if they were* an emerging part of international law. For example, in 1987, the World Commission on Environment and Development (WCED), under the leadership of the former Prime Minister of Norway, Gro Harlem Brundtland, established leading principles for the sustainable future of the land and environment (WCED 1987, Annex 1). The starting point of the WCED principles is that everyone has the fundamental right to a safe and healthy environment. Other principles address ways of ensuring the fundamental right, and thus provide guidelines for how the process of long-term stewardship might proceed (derived primarily from the WCED principles and Hunter, Salzman, and Zaelke [2002, 376–438]).

1. *First, do no harm*. States shall not cause environmental harm to other states. They are obligated to prevent and/or cease actions that may cause significant transboundary environmental harm. The minimum standard of environmental harm should be the same that is applied in the domestic context: "Do not do to others what you would not do to your own citizens."

2. *Limit the risk*. States shall take reasonable measures to reduce environmental dangers when science may be undecided as to the causes as well as the effects of threats to the environment (known as the "precautionary principle").

3. *Maintain sustainability*. States shall respect a functional biosphere by maintaining ecosystems, preserving biological diversity, and ascertaining the optimum sustainable yield in the use of living natural resources.

4. *Ensure environmental protection*. States shall establish the necessary and sufficient standards for protecting the environment, and provide procedures for environmental impact assessment and public disclosure of relevant data on environmental quality.

5. *Promote intergenerational equity*. States shall manage environmental needs for the benefit of present and future generations. The principle projects a need to balance present environmental concerns with the demands of the future.

6. *Treat the environment as a common heritage*. States shall recognize that vulnerable ecosystems are part of the global commons.

7. *Co-operate on environmental issues*. States are obligated under international law to co-operate on matters of common concern. Applied to the environment, co-operation among states includes:
   a. reasonable and equitable use of transboundary resources
   b. cessation of activities that breach international environmental obligations and compensation for harm done
   c. fair and equal treatment of those affected by transboundary environmental activities
   d. exchange of information on transboundary natural resources and consultation on environmental threats
   e. assessment and prior notification of environmental impact of activities with significant transboundary effects
   f. joint efforts in scientific research and monitoring environmental issues
   g. development of contingency plans for environmental emergencies
   h. peaceful settlement of environmental disputes

8. *Differentiate the environmental needs of states.* States shall recognize common but differentiated responsibilities regarding the environment. Assistance to developing countries in support of environmental protection and sustainable development may be critical in meeting global environmental threats.

Student Activity

Develop a long-term stewardship plan for monitoring and assessing the environmental risk that you identified in Part III.

Summary

The critical question for the development of science and society in the Arctic is "What do we need to know in order to live well in this vast region?" The sensitivity and vulnerability of high-latitude ecosystems require that science and society be understood as interrelated processes. The framework for analysis suggested in this Lecture establishes a systematic basis for the application of science to environmental challenges in the Arctic.

The **atmospheric sciences** provide insight into global climate patterns, and explain why the Arctic is susceptible to accumulation of an undue share of contamination from other areas of the world. The **ocean sciences** reveal the major effect of ocean warming and cooling on climate change, especially over the entire northern hemisphere. The drift of water and sea ice affects the future of marine wildlife, the economy, and infrastructure in the circumpolar North. With the help of **Earth sciences,** important phenomena of life in the North may be understood—for example, earthquakes, tsunamis, and permafrost. The Earth system encompasses slow change and catastrophic processes as well as the complex interactions between geological, chemical, and biological phenomena, or biogeochemical cycles. The hydrological cycle, for example, explains the occurrence of permafrost in the circumpolar North. **Ecosystem sciences** explain the complex interactions between living organisms and biogeochemical cycles, including the hydrological, carbon, nitrogen, and phosphorus cycles. Knowledge of the carbon cycle, for example, is essential for understanding the role of carbon dioxide in controlling the Earth's climate. Ecosystems analysis emphasizes interrelationships of widely diverse phenomena, including food webs, toxin accumulations, adaptations to environmental change, and human health issues.

The primary environmental challenges of the circumpolar North are resource depletion and environmental contamination. The development of science-based policy is especially relevant to the circumpolar North in order to manage the risks and human impacts associated with the unique vulnerability of the region. A case study of Amchitka Island demonstrates how radionuclide contamination may destroy the components of an ecosystem and threaten the livelihood of cultures that depend on subsistence. As an approach to ensuring sustainability through long-term stewardship, a guide is offered that draws on major principles of ecology and international law.

Study Questions

1. List five environmental terms and discuss how they are specifically applicable to the Arctic.

2. What is a useful method for analyzing land and environment in the Arctic?

3. In what ways does the atmosphere connect the Arctic to the activities in other parts of the globe?

4. What role does the ocean play in global climate change?

5. How does water move or, more precisely, cycle through the Arctic ecosystem?

6. How do biogeochemical cycles interact with ecosystem functions?

7. In what ways is the Arctic vulnerable to ecological contamination and resource depletion?

8. How do environmental changes affect human health and culture?

9. Discuss how the major principles of ecology help to achieve long-term stewardship?

10. In what ways does international environmental law support sustainable development?

Glossary of Terms

Arctic haze	a haze produced by particulate matter, primarily sulphur, which becomes trapped in regions of the Arctic that experience inversions. The pollution that comprises the particulate matter is primarily from Subarctic sources but becomes trapped in the Arctic because of the cool temperatures.

biocomplexity	the complex web of interrelationships between biological, chemical, social, and economic systems.
biodiversity	the diverse forms in which organisms evolve based on adaptation, distribution, and habitat and their interactions.
biogeochemical cycle	the cycle of nutrients through living and non-living reservoirs. The most important cycles are the hydrological cycle, carbon cycle, nitrogen cycle, and phosphorus cycle.
carbon cycle	the movement of carbon from the internal Earth to the atmosphere and to the ocean, soil, and living organisms. Carbon does not return directly to the atmosphere; rather, it is stored for long periods in limestone and fossil fuels. With the breakdown of such substances it is released back into the atmosphere.
carrying capacity	the maximum population that can be supported by a given ecological region.
complex systems	environmental relationships and feedbacks that occur on different scales of time, locale, and organization.
deposition	particulate matter that is removed from the atmosphere and deposited on the land or ocean. Dry deposition is dust or sand that is carried in the winds and subsequently deposited. Wet deposition is rain, snow, or hail that carries particulate matter from the atmosphere to the land or ocean surface.
ecosystem	a holistic concept of the plants, the animals habitually associated with them, and all the physical and chemical components of the immediate environment or habitat that together form a recognizable self-contained entity.
glacier	rivers or sheets of ice that last year-round and flow slowly, carving the landscape and depositing large volumes of sediment. Alpine glaciers form in or adjacent to mountain regions. Continental glaciers, or ice sheets, are vast layers of ice that spread over thousands of square kilometres of continental crust.
gyre	the flow of oceanic currents in large, rotating loops caused by a combination of the forces of the Earth’s rotation.
hydrological cycle	the overall circulation of water from reservoir to reservoir in the Earth system.

ice fog	a phenomenon in cold regions in which particulate matter, encompassed by a small water droplet, freezes and remains suspended in air, creating a fog. Ice fog occurs as the result of inversions in many localized regions of the Arctic.
mid-ocean ridge	a location on the ocean floor where two or more tectonic plates are moving away from each other, allowing the introduction of magma.
nitrogen cycle	the overall circulation of nitrogen from reservoir to reservoir in the Earth system.
North Atlantic Oscillation	pools of warm and cool surface water that circle the North Atlantic region. The distribution of the pools directly affects climate conditions in northern Europe.
organizational scale	variation in the degree of structural complexity.
ozone	the molecule O_3. In the stratosphere, ozone blocks most of the UV-B radiation from the Sun. In the troposphere, ozone is a major component of smog.
Pacific Decadal Oscillation	a change of current associated with changes in atmospheric pressure, winds, precipitation, and water temperature in the Pacific Ocean. The changes seem to be occurring in ten-year periods.
phosphorus cycle	the overall circulation of phosphorus from reservoir to reservoir in the Earth system.
photosynthesis	the synthesis of sugars and other organic compounds from sunlight by primary producers.
plate tectonics	the theory that the Earth's crust is in constant motion, rearranging the semi-rigid crust and upper mantle (lithosphere) over the partially fluid section of the mantle (asthenosphere).
predation	the pathway by which contaminants move from animal to animal in regional food webs.
primary productivity	the amount of light energy converted to chemical energy by primary producers.
radionuclide	an unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.
spatial scale	variations in size and position of locale where phenomena and processes occur.
subduction zone	location on the Earth's surface where a crustal plate and an oceanic plate meet, causing the oceanic plate to be pushed back into the Earth's mantle by the crustal plate.

sulphur cycle	the overall circulation of sulphur from reservoir to reservoir in the Earth system.
sustainability	the maintenance of an ecologically sound, economically feasible, and socially just biosphere.
temporal scale	variation in the time frame of existence of phenomena and processes on Earth.
trophic level	a level in a food chain, distinguished by the method of obtaining food.

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